OPTICAL ELEMENT, METAL DIE, AND CUTTING TOOL

BACKGROUND OF THE INVENTION

This invention relates to an optical element having diffractive grooves, a metal die for forming it, and a cutting tool for the die, and in particular, to an optical element with a reduced loss of light quantity to make the effective light quantity near to 100%, and a metal die and a cutting tool for obtaining an ideal diffractive optical element by taking into consideration factors such as a shape of diffractive grooves, surface roughness, conditions of working the metal die, a tool for working the metal die, resin material.

A diffraction optical element is an optical element such that sawtooth shaped steps are provided on an optical surface of an optical element, diffraction is generated by varying the phase of a light wave passing there, to utilize

the function to deflect the optical path. For a bundle of rays refracted by a basic aspherical shape, by further deflecting the optical path by the effect of diffraction, it can exhibit with a single optical surface a diffraction effect equivalent to that with two optical surfaces. On top of it, an optical path is more difficult to be deflected the longer the wavelength is in the case of refraction, but an optical path through diffraction is more deflected the longer the wavelength is; therefore, the wavelength dependency of refraction can be reduced by combining the both.

For an example of application of a diffractive lens, an image-sensing lens for a camera provided in a personal computer, a pickup optical element for an optical disk etc. can be cited. The former can make chromatic aberration smaller efficiently with a small number of lens pieces by using diffraction effect; therefore, it actualizes an image-sensing lens which is thin, of light weight, and convenient for being provided in a personal computer. Further, for an example of the latter, it can be cited an objective lens which is used in correcting the aberration owing to the wavelength fluctuation of a high-output laser diode as a light source which is generated at the time of writing information after it is read out from an optical disk such as a DVD or a CD.

Further, in order that different optical disks such as a DVD and a CD may commonly use a single optical element, an optical element utilizing a diffraction effect is employed to correct satisfactorily aberration for a plurality of light-source wavelengths and to secure satisfactory chromatic aberration characteristics against wavelength fluctuation owing to temperature variation and a mode hop.

However, in the case of the former lens, if scattering is produced on an optical surface or inside a lens, a flare appears in the formed image to reduce the contrast, which deteriorates the image quality sharply. Especially in the case of a diffractive lens, because of the discontinuous optical surface, it is difficult in designing the lens to make diffraction efficiency 100% for whole incident light in the angle of view, and it has a characteristic such that a certain amount of scattering is produced even if it is ideally produced.

Accordingly, in manufacturing a diffractive lens, in order to reduce scattering by the lens to a level practically of no problem, it is more important than a case of a usual lens to generate the shape of its optical surface which is nearest to the designed shape as much as possible. As for the level of scattering of no practical problem, a level not higher than 5% of incident light quantity, or more desirably

a level not higher than 3% is required. This is equivalent

to the surface reflectivity of an optical surface made of the

representative optical glass such as BK7 in the case where it

has not been coated with a reflection reducing coating, and

it is the criterion in asking for a necessary image quality

and a merit of employing a diffractive optical surface that

the loss of light quantity by scattering is at least not more

than that by reflection in the state of no reflection

reducing coating.

   Further, in the case of the latter optical element in a

pickup system for an optical disk, because the shortening of

life and lowering of reliability are generally more

remarkable, the higher power a laser diode outputs, it is

preferable to use a laser diode at a low output as much as

possible; therefore it is necessary to reduce the loss of

light quantity such as scattering in the optical path as much

as possible in order to secure a sufficient light quantity in

writing.

   For a permissible range of the above-mentioned light

quantity loss, it is usually obtained a value not larger than

10% of the remainder when an incident light quantity is

subtracted by the surface reflection component, or more

desirably, a value not larger than 5% of it. This value is

empirically obtained by synthesizing such factors as the alignment of the optical element, the light quantity dispersion of laser diodes, the sensitivity dispersion of light receiving devices.

As described in the above, in an optical element utilizing diffraction, as compared to a usual optical element having a continuous optical surface, an influence of scattering etc. is easy to be produced remarkably; accordingly, it is important to obtain an ideal diffraction efficiency without loss of light quantity by scattering, and for that purpose, first of all, it should be mentioned that a diffractive optical surface must be produced in such a manner as to have an ideal shape.

However, in the manufacturing of a conventional diffractive optical element, it is not clear what degree of an error would be practically of no problem for the above-mentioned ideal shape, and in the case where a metal die for forming and transferring a diffractive optical surface is cut-worked, also with respect to the shape of the cutting part of a tool, only it is known that the edge should be made sharp, but it is not clear that to what degree the edge should be sharpened, or what kind of a side effect is produced when it is made sharp.

Further, there has been no idea such that the apex

angle of a tool required should be made definite by taking

into consideration the parallelism of the step section of

diffractive grooves to the incident bundle of rays. Further,

also it has not been clear a threshold value of surface

roughness to reduce scattering sufficiently at the portion of

an optical surface other than the step sections of

diffractive grooves. Also for the material to make up the

transfer optical surface of a metal die, there has not been a

concept that a high-machinability material is necessary in

order to maintain the sharp edge of a cutting tool by

reducing the wear during working. Because of that, the

sharpness of the corner of a cutting part of a tool becomes

dull only by cut-working a small number of metal dies. As

the result, generation of an ideal shape of diffractive

grooves is made impossible, and the following problems have

been frequently observed, which are that scattering of an

incident bundle of rays is brought about, taking more time

for working the optical surface of a metal die than

necessary, that scattering becomes larger by an insufficient

precision of working, etc.

SUMMARY OF THE INVENTION

This invention was performed by considering main causes of the above-mentioned points, and it is an object of the invention to provide a metal die capable of actualizing the manufacturing of a diffractive optical element having a good efficiency, a tool for the die, and an optical element manufactured by the die.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a cross-sectional view of an optical element according to this invention;

Fig. 2 is an enlarged cross-sectional view in the direction of the optical axis showing a portion near one of the diffractive grooves of an optical element;

Fig. 3 is a perspective view showing a double or triple spindle super-precision lathe;

Fig. 4 are drawings showing a tool for cutting a metal die; Fig. 4(a) is a perspective view, Fig. 4(b) is the front view of the cutting part, and Fig. 4(c) is the side view of the cutting part;

Fig. 5 is a graph showing the lowering of diffraction efficiency for a single light-source wavelength in a sawtooth-shaped diffractive optical surface of a flat plate, when diffractive grooves are cut-worked by using a tool

having the arc-shaped corner of the cutting part in working

the metal die;

Fig. 6 is a drawing showing the relation between

wavelength used taken for the abscissa, and the diffraction

efficiency of an optical element taken for the ordinate;

Figs. 7(a) to 7(c) are drawings showing the relation

between setting positions of a metal die and a tool at the

time of cut-working;

Fig. 8 is a drawing showing the relation between a tool

70 and a metal die 50 during cutting by a lathe;

Fig. 9 is a drawing showing a cross-section of a metal

die; and

Fig. 10 is a perspective view of a new tool according

to this invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

An optical element as set forth in (1) is an optical

element which comprises, at least in a part of an optical

surface, diffractive grooves (the first groove as counted

from the optical axis is not included) provided with at least

a first surface approximately expressed by a specified

optical function and a second surface extending to the

direction crossing said first surface, and is capable of

transmitting light, wherein said first surface and said

second surface of said diffractive grooves are connected by a

third surface which is not approximately expressed by said

optical function, said second surface is parallel to the

optical axis with an angular error not greater than 1°, and

the width of said third surface in the direction

perpendicular to the optical axis is not smaller than 0.5%

and not larger than 15% of the sum of the width of said

first surface connected to it in the direction perpendicular

to the optical axis and the width of said third surface in

the direction perpendicular to the optical axis; therefore,

scattering of an incident bundle of rays is suppressed to the

utmost, and transmitted light quantity can be raised.

This invention will be explained in more detail by

referring to the drawings. Fig. 1 is a cross-sectional view

of an optical element, and Fig. 2 is an enlarged cross-

sectional view in the direction of the optical axis showing a

portion near one of the diffractive grooves. In Fig. 2, the

optical element 10 comprises an optical surface 10a at the

left side in the drawing. On the optical surface 10a, one of

the diffractive grooves 14 is formed. The diffractive groove

14 is formed of the first surface 11 which is approximately

expressed by a basic aspherical surface and a phase

difference- or an optical path difference-function, the

second surface 12 which is parallel to the optical axis with
an angular error not larger than 1°, and the third surface 13
which connects these. The width $\Delta 1$ of the third surface in
the direction perpendicular to the optical axis is not
smaller than 0.5% and not larger than 15% of the sum of the
width $\Delta 2$ of said first surface 11 connected to it in the
direction perpendicular to the optical axis and the width $\Delta 1$
of the third surface 13 in the direction perpendicular to the
optical axis. That is, the following expression should be
satisfied:

$$(\Delta 1 + \Delta 2) \times 0.5/100 \leq \Delta 1 \leq (\Delta 1 + \Delta 2) \times 15/100.$$

Because the third surface 13 is not expressed approximately
by a basic aspherical surface and a phase difference- or
optical difference-function, it is a region not concerning
the improvement of the optical performance of the optical
element 10; hence, it should be narrow as much as possible.
However, because the corner of the cutting part of a tool has
a certain size, in manufacturing a metal die, a surface of
the metal die corresponding to the third surface 13 is
inevitably formed. Therefore, by making this surface small
to the utmost, the third surface is controlled to be narrow
as described in the above, by which the transmitted light

quantity through the optical element 10 is secured
sufficiently.

As shown in Fig. 1 and Fig. 2, the shape of the
diffractive grooves has a shape which has steps and is
patched and darned with aspherical surfaces, and because a
bundle of rays from a light source produces phase differences
owing to these steps to generate diffraction, a function to
deflect the path of the transmitted light in a specified
direction is produced. If a bundle of rays transmitted
through this diffractive optical surface has a light quantity
equal to 100% of a value which is obtained by subtracting
the surface reflection component owing to the refractive
index difference from the incident bundle of rays, the
diffraction efficiency is 100%, but actually the diffraction
efficiency does not become 100% owing to several factors.

Next, a method of working a metal die for forming and
transferring diffractiive grooves of a diffractive optical
element will be shown. In Fig. 3, a perspective view of a
double or triple spindle super-precision lathe is shown.
Fig. 4 is a drawing showing a tool for cutting a metal die;
Fig. 4(a) is a perspective view of it, Fig. 4(b) is the front
view of the cutting part, and Fig. 4(c) is the side view of
the cutting part.

In Fig. 3, on a spindle slide table 102 which is supported on a base plate 100 and capable of moving in the Z direction, an air spindle 103 is disposed, to support a metal die 50 in a manner capable of rotation. On the other hand, at this side of the spindle slide table 102, a tool table which is capable of moving in the X direction is disposed, to support a tool 70.

As the metal die 50 is being rotated by the air spindle 103, the surface of the metal die 50 corresponding to the diffractive grooves of an optical element is cut-worked with a diamond tool 70 with a shape of a bayonet having its corner of the cutting part sharply pointed as shown in Fig. 4. Because it is usually required that the shape error in working an aspherical shape is not greater than 50 nm, it is more general to carry out the working by using a double spindle super-precision lathe which is simpler and easy to do a high-speed working than a triple spindle type for which the positional adjustment of the cutting part of a tool is complicated. Accordingly, to the shape of valleys on the metal die 50 corresponding to diffractive grooves, the shape of the corner of the tool is transferred as it is; therefore, to what degree the corner of the cutting part of the tool is sharp becomes one of the important factors influencing diffraction efficiency.

In Fig. 4, the cutting part of the tool is sharply
pointed and the corner of the cutting part converges to a
point; however, the corner of the cutting part of an actual
tool has a shape such that the corner of the rake face has a
shape of a minute arc or plane for example, or a complicated
shape produced by a minute chipping at the time of
manufacturing the tool, and has a size not smaller than
several hundreds nm. In this specification, this portion is
referred to as the third part of the cutting edge, and the
shape on an optical surface cut-formed by this portion is
referred to as the third surface.

Fig. 5 is a graph showing the lowering of diffraction
efficiency for a single light-source wavelength in a
sawtooth-shaped diffractive optical surface of a flat plate,
when diffractive grooves are cut-worked by using a tool
having the arc-shaped corner of the cutting part in working
the metal die; this graph is prepared by taking the arc
radius of the corner of the cutting part for the abscissa,
the diffraction efficiency for the ordinates, and taking
three kinds of width (pitch) values of the diffractive
grooves 10 μm, 20 μm, and 40 μm in the direction
perpendicular to the optical axis for a parameter. At the
corner radius size of the tool of 10 μm, the diffraction
efficiency is lowered to 82.3% even for the pitch of the

diffractive grooves of 40 μm, to 66.2% for the pitch of 20

μm, and 39.1% for the pitch of 10 μm, which is not shown in

the graph, to make most of the incident light scattered and

the diffraction effect impossible to expect. Even in the

case where the corner radius size of the tool is so small as

3 μm, the diffraction efficiency is 90.8% for the pitch of

40 μm, 82.3% for the pitch of 20 μm, and 65.4% for the pitch

of 10 μm, which means that 1/3 of the light quantity is

scattered still. Inversely speaking, in order to make the

quantity of scattered light not greater than 10% or 5% by

the above-mentioned criterion, it is necessary that the

corner radius of the cutting part of a tool is made to be not

greater than 3.5 μm or 1.5 μm for the pitch of 40 μm, not

greater than 1.5 μm or 0.9 μm for the pitch of 20 μm, and not

greater than 0.7 μm or 0.3 μm for the pitch of 10 μm,

respectively.

From the above description, it can be understood that,

in order to make the quantity of scattered light to be not

greater than 10% or 5%, the ratio of the width in the

direction perpendicular to the optical axis, of the groove

portion which cannot be cut to an ideal shape owing to the

corner radius of the cutting part of a tool, to the width of

the diffractive grooves in the same perpendicular direction

is at least not greater than 10%, or more desirably, not

greater than 5%.

Incidentally, there is an actual situation that, in the

case where diffraction is utilized for a plurality of light

wavelengths as described in the foregoing, diffraction

efficiency cannot be made 100% for all the wavelengths used.

Fig. 6 is a drawing showing the relation between wavelength

used, which is taken for the abscissa, and diffraction

efficiency of an optical element, which is taken for the

ordinate. The curve **a** shows the diffraction efficiency in

the case where the depth of the steps of the diffractive

grooves is designed to be such an amount as to make 100% the

diffraction efficiency at the wavelength 655 nm, which is the

wavelength of a light source for a DVD. In this case, it is

understood that, at the wavelength 785 nm, which is the

wavelength of a light source for a CD, the quantity of the

transmitted light is lowered to 91%, even though the loss

owing to surface reflection is omitted.

On the other hand, the curve **b** shows the diffraction

efficiency in the case where the depth of the steps of the

diffractive grooves is designed to be such an amount as to

make 100% the diffraction efficiency at the wavelength to be

used for a CD, and at the wavelength to be used for a DVD,

diffraction efficiency is lowered to a degree of 87.5%, and

a large amount of light quantity loss is produced.

Therefore, for a diffractive optical element to be used for a

plurality of light-source wavelengths, it is used a method

such that the designed wavelength is adjusted usually in such

a way as to make diffraction efficiency 100% at a wavelength

approximately in the middle of the both wavelengths as shown

by the curve c, to maintain a fairly satisfactory diffraction

efficiency for either of the light-source wavelengths. For

the curve c, the depth of steps of the diffractive grooves is

designed so as to make diffraction efficiency 100% at the

wavelength 720 nm, and diffraction efficiency is maintained to be

about 98% for the wavelength to be used for a DVD, and about

97% for the wavelength to be used for a CD.

Accordingly, it should be understood that even if an

ideal optical surface can be obtained, in an optical system

in which a plurality of light wavelengths are used as

described in the above, light quantity loss of about 3% is

inevitably produced for every diffractive optical surface.

On top of it, because the above-mentioned lowering of

diffraction efficiency owing to the corner radius of the

cutting part of a tool is generated in the same way as the

case of a single wavelength independently of these, it is necessary to control the corner radius of the cutting part of a tool to be smaller.

In this case, assuming that diffraction efficiency is not lower than 95%, the decrement of diffraction efficiency owing to the corner radius of the cutting part of a tool must be 2% or under, and the corner radius of a tool should be 1 μm or under for the pitch 40 μm, 0.5 μm or under for the pitch 20 μm, and 0.1 μm or under for the pitch 10 μm. The ratio of the width in the direction perpendicular to the optical axis, of the portion which is formed not to have an ideal shape owing to the size of the corner of the cutting part to the width of the grooves in the same direction is generally 8% or under.

In this specification, the shape of the corner of the cutting part of the cutting tool 70 is assumed to be an arc; however, in the case of an actual tool, the shape of the corner of a tool becomes mostly as it is formed at the time of making the apex angle by grinding, and it has not always a shape of an exact arc. However, it is not varied that the size of the corner of a tool with respect to the width of diffractive grooves influences diffraction efficiency, and it is required in order not to lower diffraction efficiency by

2% or more that the ratio of the size of corner of a tool to the width of diffractive grooves is 15% or under as described in the above, or in order to make the lowering of diffraction efficiency not larger than 1%, it is necessary to make the proportion of the non-ideal-shaped portion of diffractive grooves 8% or under. Further, because the size of the corner of the cutting part of a tool is about 0.3 μm or so for the best condition in the manufacturing process, it is understood that, assuming the proportion of non-ideal-shaped diffractive grooves is up to 15%, the minimum width of diffractive grooves is 2 μm or so.

However, an accident that the cutting part of a diamond tool is chipped during the manufacturing of the tool occurs more frequently, the sharper the corner is made; thus, in the case where the corner size of the cutting part of a tool is 1 μm or under, the yield of manufacturing tools is lowered sharply. Further, regarding a refracting surface between steps, if the corner of the cutting part of a tool is made sharper, the surface roughness is deteriorated in the case of working with the same tool feed; therefore, the amount of the generation of scattering in this portion increases. Up to this time, the corner size of the cutting part of a tool has never been checked in view of such a practical problem, but

only it is emphasized that the corner of the cutting part of a tool should be made minute for improving diffraction efficiency.

Further, in the case where a plurality of light wavelengths are used, because a shape which makes diffraction efficiency 100% for any one of the wavelengths extremely lowers diffraction efficiency for other wavelengths, no other shape can be selected than one that makes diffraction efficiency fairly sufficient for the plural wavelengths; thus, even a shape of diffractive grooves that is ideal in the designing stage does not make diffraction efficiency 100% at the wavelengths used, and the loss of transmitted light quantity of several % owing to scattering is generated. In such a situation, it is necessary to avoid the loss of transmitted light quantity in an actual optical element thoroughly, but up to this time, it has never been made definite that, for such an optical element to cope with a plurality of wavelengths, a particularly careful study is required.

An optical element set forth in (2) is characterized by it that the aforesaid specified optical function is expressed by the following equations:

$$N = INT(Ah^2 + Bh^4 + C),$$

$$X(h,N) = h^2/(r_N(1 + \sqrt{(1 - (1 + K_N)h^2/r_N^2)})) + A4_N h^4 +$$

$$A6_N h^6 + A8_N h^8 + A10_N h^{10} + \Delta N,$$

where N denotes the number of a ring-shaped zone of the
aforesaid diffractive grooves, h denotes a height from the
optical axis, X denotes a distance from a tangent plane in
the direction of the optical axis, r denotes the radius of
the curvature of the Nth ring-shaped zone, $K_N A4_N$ to $A10_N$ are
the coefficients of the aspherical surface, and $\Delta = -\lambda_0/(n -$
1) denotes the amount of the shift of the wave front on the
optical axis for $1\lambda_0$. The above equations are noted in p. 92
of "Introduction to Diffractive Optical Elements" (published
by Optronics Inc.), and the shape of a cross-section
including the optical axis can express a sawtooth-shaped
diffractive surface. In the above expression, λ_0 may be made
the manufacturing wavelength of diffraction ring-shaped
zones. In addition, it is possible to use any functions
other than the ones described in the above, so long as they
can express the shape of the diffraction surface of an
optical element.

Generally speaking, the pitch of diffractive ring-
shaped zones (the position of each of ring-shaped zones) is
defined by using a phase difference function or an optical
path difference function. To state it concretely, the phase

difference function Φb is expressed by the following

equation described in [M1] with radian taken for the unit,

and the optical path difference function ΦB is expressed by

the equation described in [M2] with mm taken for the unit.

[M1]

$$\Phi_b = \sum_{i=0}^{\infty} b_{2i} h^{2i}$$

[M2]

$$\Phi_B = \sum_{i=0}^{\infty} B_{2i} h^{2i}$$

Although the units are different, these two ways of

expression are equivalent in the sense that they both express

the pitch of diffraction ring-shaped zones. That is, for a

blazed wavelength λ (unit: mm), the coefficient of the phase

difference function b can be converted into the coefficient

of optical path difference function B by multiplying $\lambda/2\pi$ to

it, and inversely, the coefficient of the optical path

difference function B is converted into the coefficient of

the phase difference function b by multiplying $2\pi/\lambda$.

Now, for the simplicity of explanation, a diffractive

lens utilizing the first order diffraction light beam will be

explained. In the case of optical path difference function,

a ring-shaped zone is carved every time when the value of the

function exceeds an integral multiple of the blazed

wavelength λ, and in the case of the phase difference

function, a ring-shaped zone is carved every time when the

value of the function exceeds an integral multiple of 2π.

For example, it is assumed a lens which is formed of a

cylindrical-shaped body having diffractive ring-shaped zones

carved on the plane of the object side of the both planes of

the cylinder having no refracting power, and assuming that

the blazed wavelength is 0.5 μm = 0.0005 mm, the second order

coefficient of the optical path difference function (the

second power term) is −0.05 (if it is converted into the

second order coefficient of the phase difference function, it

becomes −628.3), and the coefficients of other orders are all

zero, for the radius of the first ring-shaped zone, h = 0.1

mm, and for the radius of the second ring-shaped zone, h =

0.141 mm. Further, regarding the focal length f of this

diffractive lens, it is known that, for the second order

coefficient of the optical path difference function B2 =

−0.05, f = −1/(2·B2) = 10 mm.

In the case based on the above-mentioned definition, by

making the second order coefficient of the phase difference

function or the or the optical path difference function a

value not equal to zero, it is possible to make a lens have a

power. Further, by making the coefficient other than the
second order one of the phase difference function or the
optical path difference function, for example, the fourth
order coefficient, the sixth order coefficient, the eighth
order coefficient, or the tenth order coefficient a value not
equal to zero, it is possible to control a spherical
aberration. In addition, the term "to control" as used in
the above description means to correct the spherical
aberration, which the portion having a refracting power
produces, by producing a reverse spherical aberration, or to
make the total spherical aberration have a desired value.

An optical element set forth in (3) is characterized by
it that it is a coupling lens of an optical pickup device for
use in an information recording and/or reproducing apparatus.

An optical element set forth in (4) is characterized by
it that it is an objective lens which converges a parallel
beam coming from direction of the optical axis.

An optical element set forth in (5) is characterized by
it that it is an objective lens which converges a divergent
light beam coming from the direction of the optical axis.

An optical element set forth in (6) is characterized by
it that it is a collimator.

An optical element as set forth in (7) is an optical
element which comprises, at least in a part of an optical

surface, diffractive grooves provided with at least a first

surface approximately expressed by a specified optical

function, and a second surface extending in the direction

crossing said first surface, and is capable of transmitting a

light beam from a single light source or light beams from a

plurality of light sources having different wavelengths,

wherein the Rz value of surface roughness of said first

surface is not greater than 1/10 of the used wavelengths of

said light sources; therefore, the quantity of transmitted

light can be sufficiently secured by suppressing scattering

of an incident light beam.

In addition, the minimum value of the Rz value of the

surface roughness of said first surface is not smaller than

1/1000 of the used wavelengths of said light sources.

Moreover, these Rz values of surface roughness are values

defined by JIS B0601-1994 (ISO 4287).

In the case where a metal die for an optical surface is

worked by a lathe with a cutting tool having a pointed

corner, the condition of tool feeding influences the surface

roughness of the optical surface to be generated to a large

extent. Accordingly, even though the pitch, and the

ridgelines of the peaks and valleys are approximately ideal-

shaped simply, and the diffraction efficiency is close to

ideal, a large surface roughness of the transmitting surface

would scatter an incident bundle of rays to cause the

transmitted light quantity to decrease. The scattering owing

to surface roughness is inversely proportional to the fourth

power of wavelength if it is regarded as Rayleigh scattering;

therefore, if the wavelength of a light source used is made

shorter, scattering increases sharply even for the same

surface roughness, to produce a large loss of transmitted

light quantity. Hence, it is reasonable to specify the

surface roughness of a transmitting optical surface in

accordance with the wavelength to be used, and if the Rz

value of surface roughness is not larger than 1/10 of the

wavelength, scattering exceeding 1% is not generated. The

Rz value of surface roughness is a value calculated by

subtracting the values of the lowest 5 valley points from the

values of the highest 5 peak points respectively, and

averaging out the differences, and is a reliable PV value

(maximum-minimum value) which is hard to be influenced by a

noise or an abnormal point by averaging out.

Further, in a cut-working with a diamond tool, it is

generally known that a damaged layer having a depth of about

1 nm on the worked surface is formed by the cutting force

during working, and in this damaged layer, because the

arrangement of atoms is varied from the state before working,

it is very difficult to control the surface roughness of

working under the thickness of this damaged layer. Hence,

the lowest limit value of the Rz-value of surface roughness

is about 1/1000 in terms of the wavelength to be used.

In an optical element set forth in (8), the aforesaid

specified optical function is characterized by it that it is

expressed by the following equations:

$N = INT(Ah^2 + Bh^4 + C)$,

$X(h,N) = h^2/(r_N(1 + \sqrt{(1 - (1 + K_N)h^2/r_N^2)})) + A4_Nh^4 +$

$A6_Nh^6 + A8_Nh^8 + A10_Nh^{10} + \Delta N$,

where N denotes the number of a ring-shaped zone of the

aforesaid diffractive grooves, h denotes a height from the

optical axis, X denotes a distance from a tangent plane in

the direction of the optical axis, r denotes the radius of

the curvature of the Nth ring-shaped zone, K_NA4_N to $A10_N$ are

the coefficients of the aspherical surface, and $\Delta = -\lambda_0/(n -$

1) denotes the amount of the shift of the wave front on the

optical axis for $1\lambda_0$.

In an optical element set forth in (9), the aforesaid

second surface is characterized by it that it is parallel to

the optical axis with an angular error not greater than 1°.

An optical element set forth in (10) is an optical

element as set forth in any one of structures (7) to (9)

characterized by it that it is a coupling lens of an optical

pickup device for use in an information recording and/or reproducing apparatus.

An optical element set forth in (11) is characterized by it that it is an objective lens which converges a parallel light beam coming from the direction of the optical axis.

An optical element set forth in (12) is characterized by it that it is an objective lens which converges a divergent light beam coming from the direction of the optical axis.

An optical element set forth in (13) is characterized by it that it is a collimator.

A metal die set forth in (14) is a metal die which comprises, at least in a part of an optical surface, diffractive grooves provided with at least a first surface approximately expressed by a specified optical function, and a second surface extending in the direction crossing said first surface, and is used in forming an optical element capable of transmitting a light beam by molding, wherein the surface of said metal die corresponding to at least said first surface of said optical element is formed by rotary cut-working, and the amount of feed of a cutting tool in the radius direction at the time of working falls within a range from 0.1 μm to 1 μm per one rotation of said metal die; therefore, the quantity of transmitted light can be

sufficiently secured by suppressing scattering of an incident light beam.

Fig. 7 are drawings showing the relation between setting positions of a metal die and a tool at the time of cut-working. The Rz value of surface roughness that is obtained when a refracting optical surface is cut-worked by an actual cut-working is varied in accordance with the way of setting a tool as shown in Fig. 7. Fig. 7(a) shows the case of an offset angle of 0° where a tool is set in such a way that the central line of the tool becomes parallel to the optical axis of the optical surface of the metal die; in this case, the step section of diffractive grooves become conical around the optical axis, and in particular, for an infinite incident bundle of rays, optically unnecessary part is produced. Fig. 7(b) shows the case where a tool is set with an offset angle of $\alpha/2$ to right in such a way that the one of the flanks making the apex angle α of the tool becomes parallel to the optical axis in order to make the step section of the diffractive grooves parallel to the optical axis. As clearly understood from the both drawings, in the relation shown in Fig. 7(a), the Rz value is theoretically $P/2\tan\{\alpha/2\}$ for an amount of feed per one rotation of the metal die P (called a feed rate also), and in the relation

shown in Fig. 7(b), $Rz = P/\tan\alpha$ is given. In this case, if

the tool apex angle α is as small as 10° or under, the

difference between the Rz values for both cases can be

regarded approximately as zero, because $2\tan(\alpha/2) \cong 2 \times \alpha/2 =$

$\alpha \cong \tan\alpha$.

However, such a small apex angle of a tool is actually

not general, because it causes chipping of the cutting part

frequently to occur during manufacturing of a tool, and

breakage of the cutting part during cut-working is easy to be

generated. Further, it does not lower also the Rz value

itself. Usually, it is general that the apex angle of a tool

is determined to be about 30 to 40° with the above-mentioned

things taken into consideration, and the Rz values for these

cases are compared in the table shown in Fig. 7(c). It is

understood that surface roughness is improved for the

relation of Fig. 7(b) by 7.5% at the tool apex angle 30° and

almost 15% at the tool apex angle 40° than the case shown in

Fig. 7(a). Further, to state it inversely, for obtaining the

same value of the surface roughness Rz, the tool setting

shown in Fig. 7(b) can perform cut-working with a feed rate P

faster by 7.5 to 15% than the relation of Fig. 7(a);

therefore, working of a die can be performed with a higher

speed and better efficiency.

Now, surface roughness Rz will be explained. In an
example of an objective lens for a pickup device employing a
conventional refracting lens or a collimator, for the used
wavelength 650 nm, the surface roughness Rz of an optical
surface was about 50 nm, and the loss of light quantity of
the formed lens owing to the surface scattering was 1% or
under. From this fact, it is understood that the loss of
light quantity owing to Rayleigh scattering can be reduced to
an almost negligible degree, if the surface roughness Rz of a
lens which is formed by an optical surface of a metal die
cut-worked with a diamond tool.

Further, in order to obtain a better surface roughness,
it is appropriate to make small the above-mentioned amount of
feeding a tool per one rotation of an optical surface of a
metal die (feed rate) P, by lowering the speed of feeding the
tool during the cut-working of an optical surface. However,
to make the feed rate P small means to prolong the time for
cut-working, and about 1/10 times of the present feed rate is
practically a limit for the reason of productivity. Because
the surface roughness value Rz of an optical element which is
cut-worked with a tool having a pointed corner is
proportional to the feed rate P as shown in Fig. 7(c), the Rz
value obtained by a cut-working in this condition is about
1/100 of the wavelength of the used light source, as it is

1/10 of the above-mentioned value. To summarize the above-mentioned, in order to eliminate the influence of light quantity loss owing to Rayleigh scattering, only it is necessary to make Rz value 1/10 or under of the wavelength of the used light source, and practically it is desirable to make it not smaller than 1/100 at the same time.

Incidentally, in the cut-working of the optical surface of a metal die with a tool, if it is supposed to be obtained, the feed rate P to satisfy the condition for making the Rz value fall within a range from 1/1000 to 1/10 of the wavelength of the used light source as described in the above, assuming that the wavelength of the used light source is 650 nm, and a tool having the apex angle of the cutting part 30° is set at an offset angle of 15° as shown in Fig. 7(b), the feed rate falls within a range from 3.75 nm/rev to 37.5 nm/rev This is a value in the case where the corner of the cutting part of the tool makes a perfect apex, and it is understood that an extremely lower feed rate is necessary as compared with a usual feed rate which is from 2 to 4 μm/rev Because such a low feed rate value gives too low a productivity in the actual working of metal dies, it is of no practical use in the case where a mass of metal dies are necessary.

However, in the case of the corner of the cutting part of an actual straight turning tool, there is a limit in making it sharp for the reasons of yield in manufacturing and efficiency, to result in a minute round-shaped corner in most cases. In some cases, even chamfering is done by cutting off the corner of the cutting part intentionally in order to prevent breakage. As described in the above, in a situation such that there is a minute arc at the corner of the cutting part, the feed rate value can be remarkably improved as described below, with the surface roughness of working suppressed to a low value.

The following relation is known between the feed rate P in the case where corner radius R is given to the corner of the cutting part and the surface roughness Rz of working:

$Rz = R(1 - \cos\phi)$, where $\phi = \sin^{-1}(P/2R)$ ----(eq.1).

On the basis of this, the values of the feed rate P, which are obtained for Rz values at $\lambda = 650$ nm, including the case where the corner of the cutting part is an apex, are shown in the following [Table 1]. For the corner radius R of the cutting part, diffraction efficiency is improved sharply for R values of 3 μm or under as shown in Fig. 5 too, and for R values of 1 μm or under, the improvement of diffraction efficiency accompanied by its getting further minute becomes

gentle. Therefore, in this invention, it is specified the
case where the corner of the cutting part lies at a distance
from the position of the virtual apex point within a range
from 0.1 μm to 3 μm with the cases where the apex angle α is
up to 90° taken into consideration, including the case where
the corner of the cutting part is not round. On the other
hand, from the practical view point to reduce the lowering of
yield owing to chipping during manufacturing of a tool and
the wear by grinding, efficiency, etc., and chipping during
actual cut-working and breakage of the corner of the cutting
part, it is said that the limit of the corner radius R of the
cutting part is about 0.3 μm; therefore, it can be said that
the range of the corner radius R of the cutting part from 0.3
μm to 0.5 μm is an optimum range to keep diffraction
efficiency high and to make a stable supply and working
possible. Assuming that the apex angle of the cutting part
has a general value, which is about 40°, including also the
above-mentioned case where the corner of the cutting part is
not round, for a more desirable range, it can be considered
that the corner of the cutting part lies at a distance from
the virtual apex point falling within a range from 0.2 μm to
1.5 μm. The following [Table 1] shows the values of the feed

rate P which are calculated for the above-mentioned range with the corner radius R of the cutting part varied.

Table 1

Edge end R	$Rz = \lambda/10$	$Rz = \lambda/100$
R = 0	37.5 nm/rev	3.8 nm/rev
R = 0.1 μm	137.0 nm/rev	57.7 nm/rev
R = 0.3 μm	241.0 nm/rev	111.0 nm/rev
R = 0.5 μm	361.0 nm/rev	147.0 nm.rev

Now, if the case where the corner radius R of the cutting part is 0.3 μm, which is a limit value in manufacturing a tool, is compared with the case where the corner radius R is zero, that is, an ideal apex, for obtaining the surface roughness Rz value $\lambda/100$ (6.5 nm), the difference in feed rate is more than 15 times, and this as itself directly indicates that the corner of the cutting part being made 0.3 μm can improve the efficiency of cut-working of a metal die by more than 15 times. Further, it is understood by this that the corner radius R of the cutting part 0.3 μm means not only the limit from the view point of the yield of manufacturing and the efficiency, but also the limit of minuteness in cut-working for the reasons of suppressing Rayleigh scattering and securing a practical

productivity. To summarize the above-mentioned things, in the case where an optical surface of a metal die is cut-worked with a straight turning tool, it is ideal to determine the feed rate in accordance with the size of the corner radius R of the cutting part, but it is necessary to make it at least 1 μm/rev or under and it is desirable to make it 100 nm/rev or over.

An equivalent corner radius R of the cutting part is obtained from a distance D from the apex of the cutting part to a position including the whole corner edge. In respect of a corner edge of a straight turning tool which lies within the distance D from the virtual apex of the cutting part, the shape of the corner edge is not always an arc; however, by substituting for the shape an equivalent arc whose size is not so much different from the size of the front edge of the cutting part for generalization, a value of criterion for a surface roughness Rz of working and a feed rate which is a condition of cutting can be obtained. Now, this equivalent corner radius R of the cutting part is to be obtained by the following equation:

$$R = D \cdot \tan(\alpha/2) \qquad\qquad (eq.2),$$

where α denotes the apex angle of the cutting part.

In a metal die set forth in (15), the aforesaid second surface is characterized by it that it is parallel to the optical axis with an angular error not greater than 1°.

An optical element set forth in (15) is characterized by it that said optical element is formed by injection molding or by injection compression molding using a metal die as set forth in (14) or (15).

In an optical element set forth in (17), the aforesaid specified optical function is characterized by it that it is expressed by the following equations:

$$N = INT(Ah^2 + Bh^4 + C),$$

$$X(h,N) = h^2/(r_N(1 + \sqrt{(1 - (1 + K_N)h^2/r_N^2)})) + A4_N h^4 + A6_N h^6 + A8_N h^8 + A10_N h^{10} + \Delta N,$$

where N denotes the number of a ring-shaped zone of the aforesaid diffractive grooves, h denotes a height from the optical axis, X denotes a distance from a tangent plane in the direction of the optical axis, r denotes the radius of the curvature of the Nth ring-shaped zone, $K_N A4_N$ to $A10_N$ are the coefficients of the aspherical surface, and $\Delta = -\lambda_0/(n - 1)$ denotes the amount of the shift of the wave front on the optical axis for $1\lambda_0$.

An optical element set forth in (18) is characterized by it that it is a coupling lens of an optical pickup device

for use in an information recording and/or reproducing
apparatus.

An optical element set forth in (19) is characterized
by it that it is an objective lens which converges a parallel
light beam coming from the direction of the optical axis.

An optical element set forth in (20) is characterized
by it that it is an objective lens which converges a
divergent light beam coming from the direction of the optical
axis.

An optical element set forth in (21) is characterized
by it that it is a collimator.

A tool set forth in (22) is a tool for cutting a metal
die to be used in forming by molding an optical element which
comprises, at least in a part of an optical surface,
diffractive grooves provided with a first surface expressed
approximately by a specified optical function, a second
surface extending in the direction crossing said first
surface, and a third surface connecting said first surface
and said second surface, and is capable of transmitting
light, wherein at least a part of the surface of said metal
die is formed by rotary cut-working using said tool, the rake
face of said tool, which is opposite to the rotating
direction of said metal die during said rotary cut-working,
is outlined by a first part of the cutting edge which cut-

forms the surface of said metal die corresponding to said

second surface of said optical element, a second part of the

cutting edge extending in the direction crossing said first

part of the cutting edge, and a third part of the cutting

edge which cut-forms the surface of said metal die

corresponding to said third surface of said optical element,

and the distance from the intersecting point of an extended

line of said first part of the cutting edge and an extended

line of said second part of the cutting edge to said third

part of the cutting edge is from 0.1 μm to 3 μm; therefore,

by an optical element formed by a metal die which is cut with

the above-mentioned tool, transmitted light quantity can be

sufficiently secured by suppressing scattering of an incident

light.

This invention will be explained in more detail by

referring to the drawings. Fig. 8 is a drawing showing the

relation between a tool 70 and a metal die 50 during cutting

by a lathe. In Fig. 8, the metal die 50 has its three

surfaces formed with the tool 70, that is, a first surface

11' corresponding to the first surface of diffractive grooves

of an optical element which is expressed approximately by a

specified optical function, a second surface 12'

corresponding to the second surface which is approximately

parallel to the optical axis, and a third surface 13'

corresponding to the third surface connecting these. In this working, the rake face 74 of the tool 70 which is opposite to the rotating direction of the metal die 50, is outlined by a first part of the cutting edge 71 which cut-forms the surface 12' of the metal die 50, a second part of the cutting edge 72 extending in the direction crossing the first part of the cutting edge 71, and a third part of the cutting edge 73 which cut-forms the surface 13' of the metal die, and the distance $\Delta 3$ from the intersecting point of an extended line of the first part of the cutting edge 71 and an extended line of the second part of the cutting edge 72 to the part of the cutting edge 73 falls within a range from 0.1 μm to 3 μm; therefore, the surface 13' of the metal die 50 is controlled to be small, and by an optical element formed by the metal die 50 which is cut with this tool 70, transmitted light quantity can be sufficiently secured by suppressing scattering of an incident light.

A metal die set forth in (23) is characterized by it that it is worked with a tool as set forth in (22).

In a metal die set forth in (24), the aforesaid second surface is characterized by it that it is parallel to the optical axis with an angular error not greater than 1°.

An optical element set forth in (25) is characterized by it that it is formed by injection molding or by injection compression molding using a metal die as set forth in (23) or (24).

In an optical element set forth in (26), the aforesaid specified optical function is characterized by it that it is expressed by the following equations:

$$N = INT(Ah^2 + Bh^4 + C),$$

$$X(h,N) = h^2/(r_N(1 + \sqrt{(1 - (1 + K_N)h^2/r_N^2)})) + A4_N h^4 + A6_N h^6 + A8_N h^8 + A10_N h^{10} + \Delta N,$$

where N denotes the number of a ring-shaped zone of the aforesaid diffractive grooves, h denotes a height from the optical axis, X denotes a distance from a tangent plane in the direction of the optical axis, r denotes the radius of the curvature of the Nth ring-shaped zone, $K_N A4_N$ to $A10_N$ are the coefficients of the aspherical surface, and $\Delta = -\lambda_0/(n - 1)$ denotes the amount of the shift of the wave front on the optical axis for $1\lambda_0$.

An optical element set forth in (27) is characterized by it that it is a coupling lens of an optical pickup device for use in an information recording and/or reproducing apparatus.

An optical element set forth in (28) is characterized
by it that it is an objective lens which converges a parallel
light beam coming from the direction of the optical axis.

An optical element set forth in (29) is characterized
by it that it is an objective lens which converges a
divergent light beam coming from the direction of the optical
axis.

A tool set forth in (31) is a tool for cutting a metal
die to be used in forming by molding an optical element which
comprises, at least in a part of an optical surface,
diffractive grooves provided with a first surface expressed
approximately by a specified optical function, a second
surface extending in the direction crossing said first
surface, and a third surface connecting said first surface
and said second surface, and is capable of transmitting
light, wherein at least a part of the surface of said metal
die is formed by rotary cut-working using said tool, the rake
face of said tool, which is opposite to the rotating
direction of said metal die during said rotary cut-working,
is outlined by a first part of the cutting edge which cut-
forms the surface of said metal die corresponding to said
second surface of said optical element, a second part of the
cutting edge extending in the direction crossing said first
part of the cutting edge, and a third part of the cutting

edge which cut-forms the surface of said metal die

corresponding to said third surface of said optical element,

and the angle α, which is made by said first part of the

cutting edge and said second part of the cutting edge, is not

smaller than 5° and satisfies an inequity $\theta max \leq (90 - (\alpha/2 +$

$S))$ °, where θmax denotes the maximum normal angle of said

metal die corresponding to said optical surface, and S

denotes a set angle of the tool against the optical axis

(what is called an offset angle); therefore, it never occurs

that a metal die is subjected to an interference by a tool,

which makes it possible to manufacture an optical element

having a more suitable shape.

In particular, because the curvature of the optical

surface has a tendency to become stronger in the case of a

metal die for forming a high-NA lens, in some cases the

normal angle θ (the angle made by a normal and the optical

axis) of the optical surface shape becomes very large in the

neighborhood of the outermost circumference of the optical

surface shape 50a, and in this case, if a conventional tool

is carelessly used, it provably occurs that a tool

interference (an accident in which a part of a tool that is

not a cutting edge engages with the metal die) occurs. In

the following, examples of the tool interference which have been heretofore produced easily will be explained.

For the first mode of the tool interference, such an example as described below can be cited. In order not to lower diffraction efficiency, it is necessary that the step section of the diffractive grooves (the second surface 12 as shown in Fig. 2) are parallel to the incident bundle of rays. Hence, in the case where the incident bundle of rays is an infinite light beam, the step section make a cylindrical surface parallel to the optical axis. Further, in the case where the incident bundle of rays is a divergent one, a conical shape such that a step section overhangs to a degree not to produce a shadow for an incident bundle of rays is ideal; However, this shape has an undercut section at the time of forming a lens, and a problem that an optical element which has been injection-molded sticks to the metal die and cannot be released is produced. For that reason, it is desirable that the step section is parallel to the optical axis and cylindrical for these incident bundle of rays.

However, in cut-working a metal die for molding with a tool, as shown in Fig. 7(b), it is necessary to set the tool with an inclination to the direction of the outer circumference by an offset angle S (an angle equal to 1/2 of the apex angle α, for example). Accordingly, elbowroom for

the tool is 90° − (α/2 + S) only, and in order that the metal die may not interfere the tool during cut-working, a normal angle at anywhere on the optical surface must be smaller than this value. On top of it, in an actual optical element, in order that a flange portion for fixing the element may be provided integrally at the outer side in the radial direction of the optical surface, it often occurs that the optical surface is required to have a shape extended to the farther outside of the effective diameter; therefore, it is understood that, also in this extended portion which does not actually transmit a bundle of rays, the angle α must be not smaller than 5° and satisfy an inequity θmax ≤ (90 − (α/2 + S)) °, where S denotes a set angle of the tool against the optical axis. In addition, "an offset angle of a tool" means an angle made by a line which bisects equally the apex angle of the cutting part and the optical axis of the optical surface to be cut-worked.

Accordingly, if the shape function of a diffractive optical surface to be worked is known beforehand, the normal angle θ is known from its differential values; therefore, if the maximum normal angle θmax in the range of working is obtained, the apex angle αmax to become a limit up to which no tool interference occurs is obtained from the above

inequality, and a desired shape can be safely cut-worked.
However, if the apex angle of a tool is made too small, the
yield in manufacturing the tool is lowered, which makes the
price higher and lowers the stiffness; therefore, an accident
such as "bibiri" and breakage is likely to occur. For that
reason, it can be said that a degree of 10° or so for the
apex is a practical limit as a tool for a metal die to mold
an optical element. The offset angle for this apex angle
value should be 5° or over in order to make the step section
of diffractive grooves parallel to the optical axis.

A metal die set forth in (32) is characterized by it
that it is worked with a tool as set forth in (31).

A metal die set forth in (33) is characterized by it
that the aforesaid second surface is parallel to the optical
axis with an angular error not greater than 1°.

A metal die set forth in (34) is characterized by it
that grooves corresponding to the aforesaid diffractive
grooves of the aforesaid optical element are formed in an
area for which the value of the aforesaid maximum normal
angle θmax falls within a range from 40° to 70°.

An optical element set forth in (35) is characterized
by it that it is formed by injection molding or by injection

compressing molding using a metal die as set forth in any one of structures (32) to (34).

In an optical element set forth in (36), the aforesaid specified optical function is characterized by it that it is expressed by the following equations:

$N = INT(Ah^2 + Bh^4 + C),$

$X(h,N) = h^2/(r_N(1 + \sqrt{(1 - (1 + K_N)h^2/r_N^2)})) + A4_Nh^4 +$

$A6_Nh^6 + A8_Nh^8 + A10_Nh^{10} + \Delta N,$

where N denotes the number of a ring-shaped zone of the aforesaid diffractive grooves, h denotes a height from the optical axis, X denotes a distance from a tangent plane in the direction of the optical axis, r denotes the radius of the curvature of the Nth ring-shaped zone, $K_N A4_N$ to $A10_N$ are the coefficients of the aspherical surface, and $\Delta = -\lambda_0/(n - 1)$ denotes the amount of the shift of the wave front on the optical axis for $1\lambda_0$.

An optical element set forth in (37) is characterized by it that it is a coupling lens of an optical pickup device for use in an information recording and/or reproducing apparatus.

An optical element set forth in (38) is characterized by it that it is an objective lens which converges a parallel light beam coming from the direction of the optical axis.

An optical element set forth in (39) is characterized by it that it is an objective lens which converges a divergent light beam coming from the direction of the optical axis.

An optical element set forth in (40) is characterized by it that it is a collimator.

A tool set forth in (31) is a tool for cutting a metal die to be used in forming by molding an optical element which comprises, at least in a part of an optical surface, diffractive grooves provided with a first surface expressed approximately by a specified optical function, a second surface extending in the direction crossing said first surface, and a third surface connecting said first surface and said second surface, and is capable of transmitting light, wherein at least a part of the surface of said metal die is formed by rotary cut-working using said tool, the rake face of said tool, which is opposite to the rotating direction of said metal die during said rotary cut-working, is outlined by a first part of the cutting edge which cut-forms the surface of said metal die corresponding to said second surface of said optical element, a second part of the cutting edge extending in the direction crossing said first part of the cutting edge, and a third part of the cutting edge which cut-forms the surface of said metal die

corresponding to said third surface of said optical element,
in respect of a first flank which makes up said first part of
the cutting edge with said rake face, and a second flank
which makes up said second part of the cutting edge with said
rake face, the inclination angle of said first flank against
said rake face and the inclination angle of said second flank
against said rake face is different from each other, and the
difference falls within a range from 1° to 20°; therefore, it
never occurs that a metal die is subjected to interference by
a tool, which makes it possible to manufacture an optical
element having a more suitable shape. If the difference is
less than 1°, the effect is little, and if it exceeds 20°,
manufacturing of a tool becomes difficult. In addition, the
both angles of inclination mean respectively an angle made by
said first flank against a virtual plane perpendicular to
said rake face at the first part of the cutting edge and an
angle made by said second flank against a virtual plane
perpendicular to said rake face at the second part of the
cutting edge.

The second mode of the tool interference will be
explained. The shape of the diamond chip of the cutting part
of a conventional tool forms, as shown in Fig. 4, a first
clearance angle β1 by it that the flanks 75 and 76 making up

the apex angle intersect each other with an angle deviated by several degrees from the rectangle against the rake face. The tool is designed in such a manner that, by forming the second clearance face 77 further, it never occurs that the flanks 75 and 76 extend long toward lower direction to such a degree as to interfere the shape of the optical surface of a metal die. However, the first clearance angle $\beta 1$ has a limit of about 10° at the maximum because of generation of chips etc. during manufacturing of the tool, and the angles of inclination of the flanks 75 and 76 have a limit of several degrees, which depends on the apex angle α.

In a conventional tool, the inclination angles of the flanks 75 and 76 have been taken as equal for both left and right sides, which makes the shape of the edge symmetric in respect to left-and-right direction. Therefore, the inclination angle of the flanks is uniquely determined if the apex angle α is determined, and it has been put into practice that, in the case where the ridgeline of one of the flanks 75 and 76 and the second clearance face 77 generates tool interference, the angle $\beta 2$ of the second clearance face 77 is usually made to take a value falling within a range from 40° to near 50°. It is a matter of course that this lowered the strength of the cutting part and increased the frequency of

generation of "bibiri" or chips during working, which made difficult the working of a high-precision diffractive optical surface shape.

Therefore, the inventors found out that, in order to cut-work an ideal diffractive optical surface shape, if a tool is set in such a manner as shown in Fig. 7(b), in respect of the flanks in the inner circumferential side, the inclination angle 0° produces no problem at all. Accordingly, it has been found out that, because the inclination angle for the flanks in the outer circumferential side where a tool interference occurs provably can be increased to a value near two times, and owing to this, the ridgelines of the flanks 75 and 76 and the second clearance face 77 retracts more toward the center of the tool, without lowering the strength of an edge, and also without lowering the efficiency in manufacturing, a tool interference can be avoided.

A metal die set forth in (42) is characterized by it that it is worked with a tool as set forth in (41).

A metal die set forth in (43) is characterized by it that the aforesaid second surface is parallel to the optical axis with an angular error not greater than 1°.

An optical element set forth in (44) is characterized by it that it is formed by injection molding or by injection compression molding using a metal die as set forth in (43).

An optical element set forth in (45) is characterized by it that the aforesaid specified optical function is expressed by the following equations:

$$N = INT(Ah^2 + Bh^4 + C),$$

$$X(h,N) = h^2/(r_N(1 + \sqrt{(1 - (1 + K_N)h^2/r_N^2)})) + A4_N h^4 + A6_N h^6 + A8_N h^8 + A10_N h^{10} + \Delta N,$$

where N denotes the number of a ring-shaped zone of the aforesaid diffractive grooves, h denotes a height from the optical axis, X denotes a distance from a tangent plane in the direction of the optical axis, r denotes the radius of the curvature of the Nth ring-shaped zone, $K_N A4_N$ to $A10_N$ are the coefficients of the aspherical surface, and $\Delta = -\lambda_0/(n - 1)$ denotes the amount of the shift of the wave front on the optical axis for $1\lambda_0$.

An optical element set forth in (46) is characterized by it that it is a coupling lens of an optical pickup device for use in an information recording and/or reproducing apparatus.

An optical element set forth in (47) is characterized
by it that it is an objective lens which converges a parallel
light beam coming from the direction of the optical axis.

An optical element set forth in (48) is characterized
by it that it is an objective lens which converges a
divergent light beam coming from the direction of the optical
axis.

An optical element set forth in (49) is characterized
by it that it is a collimator.

A tool set forth in (31) is a tool for cutting a metal
die to be used in forming by molding an optical element which
comprises, at least in a part of an optical surface,
diffractive grooves provided with a first surface expressed
approximately by a specified optical function, a second
surface extending in the direction crossing said first
surface, and a third surface connecting said first surface
and said second surface, and is capable of transmitting
light, wherein at least a part of the surface of said metal
die is formed by rotary cut-working using said tool, the rake
face of said tool, which is opposite to the rotating
direction of said metal die during said rotary cut-working,
is outlined by a first part of the cutting edge which cut-
forms the surface of said metal die corresponding to said
second surface of said optical element, a second part of the

cutting edge extending in the direction crossing said first part of the cutting edge, and a third part of the cutting edge which cut-forms the surface of said metal die corresponding to said third surface of said optical element, in respect of a first flanks which makes up said first part of the cutting edge with said rake face, and a second flanks which makes up said second part of the cutting edge with said rake face, at least one of said flanks has a first inclination angle against said rake face, making a first clearance angle with an intersecting line of said first flank and said second flank, at least one of said first flank and said second flank further has a second inclination angle against said rake face, and at least, the flank having this second inclination angle and the other flank forms an intersecting line, which makes a second clearance angle; therefore, it never occurs that a metal die is subjected to an interference by a tool, which makes it possible to manufacture an optical element having a more suitable shape.

In order to avoid the tool interference more certainly, the inventors propose a tool having a completely new design. Fig. 10 is a perspective view of such a new tool according to this invention. In Fig. 10, the flank 75' of a tool 70' is composed of the upper flank 75a' and the lower flank 75b', and in the case where the inclination angle of the upper

flank 75a' is, for example, 5°, it is desirable that the second inclination angle of the lower flank 75b' is a value exceeding 5°.

In this way, by making the inclination angle of the flank 75' not of a single stage only, but of double stages, to form a second clearance angle $\beta2$ by the mutual intersection of the flanks owing to this inclination angle of this second stage, the above-mentioned second clearance face can be omitted. Owing to this, because the flank 75' has its portion of the first inclination angle made narrow as the thickness of the portion of the tool forming the first clearance angle and switches over to the portion of the second inclination angle <u>to form a large second clearance angle $\beta2$</u>, the tool interference can be avoided with a greater stride as compared with the conventional one. Further, the portion of the edge thickness corresponding to the first clearance angle $\beta1$, which actually has a cutting edge, has completely the same shape as a conventional one, it can be prevented that the strength of the corner edge is extremely lowered.

Further, it has a shape capable of corresponding to the above-mentioned asymmetric inclination angles of side faces; therefor, by combining these factors, it is possible to cut-

work a metal die for an optical surface having an extremely [small] <u>large</u> curvature or a high-NA lens with a sufficient elbowroom and strength.

A metal die set forth in (51) is characterized by it that it is worked with a tool as set forth in (50).

In a metal die set forth in (52), the aforesaid second surface is characterized by it that it is parallel to the optical axis with an angular error not greater than 1°.

An optical element set forth in (53) is characterized by it that it is formed by injection molding or injection compression molding using a metal die as set forth in (52).

In an optical element set forth in (36), the aforesaid specified optical function is characterized by it that it is expressed by the following equations:

$$N = INT(Ah^2 + Bh^4 + C),$$

$$X(h,N) = h^2/(r_N(1 + \sqrt{(1 - (1 + K_N)h^2/r_N{}^2)})) + A4_Nh^4 +$$

$$A6_Nh^6 + A8_Nh^8 + A10_Nh^{10} + \Delta N,$$

where N denotes the number of a ring-shaped zone of the aforesaid diffractive grooves, h denotes a height from the optical axis, X denotes a distance from a tangent plane in the direction of the optical axis, r denotes the radius of the curvature of the Nth ring-shaped zone, $K_N A4_N$ to $A10_N$ are the coefficients of the aspherical surface, and $\Delta = -\lambda_0/(n -$

1) denotes the amount of the shift of the wave front on the optical axis for $1\lambda_0$.

An optical element set forth in (55) is characterized by it that it is a coupling lens of an optical pickup device for use in an information recording and/or reproducing apparatus.

An optical element set forth in (56) is characterized by it that it is an objective lens which converges a parallel light beam coming from the direction of the optical axis.

An optical element set forth in (57) is characterized by it that it is an objective lens which converges a divergent light beam coming from the direction of the optical axis.

An optical element set forth in (58) is characterized by it that it is a collimator.

The term "diffractive grooves" as used in this specification means grooves of a relief which is provided on a surface of a lens and made to have a function to converge or diverge a bundle of rays by diffraction. For the shape of the relief, for example, it is known a shape which is formed as nearly concentric circular ring-shaped zones around the optical axis, which has a sawtooth-shaped cross-section as seen at a plane including the optical axis; such a shape is included in it.

In this specification, the term "an objective lens"
denotes, in its narrower sense, a single lens having a light-
converging function which is arranged opposite to an optical
information recording medium at the most nearest side of it
in a state in which an optical pickup device is loaded with
an optical information recording medium, or in a broader
sense, a lens group capable of moving at least in the
direction of the optical axis by an actuator together with
that single lens. In the above description, the lens group
denotes at least a single lens or more (two lenses, for
example). Hence, in this specification, the numerical
aperture NA of an objective lens of the side facing an
optical information recording medium (the image side) denotes
the numerical aperture NA of a lens surface which is
positioned nearest to and facing the optical information
recording medium. Further, in this specification, the
required numerical aperture NA denotes a numerical aperture
specified in the standard of each optical information
recording medium, or a numerical aperture of an objective
lens having a diffraction limit performance capable of
obtaining a spot diameter which is required for recording or
reproducing information for each optical information
recording medium, in accordance with the wavelength of the
light source used.

In this specification, an optical information recording medium means, for example, an optical disk of a CD type such as a CD-R, a CD-RW, a CD-Video, and a CD-ROM, or an optical disk of a DVD type such as a DVD-ROM, a DVD-RAM, a DVD-R, a DVD-RW, and a DVD-Video.

In the following, examples of practice of this invention will be explained. In addition, in respect of an offset angle, there are a case where a tool is deflected to left and a case where a tool is deflected to right; hence for these cases, it is referred to as, for example, an offset angle of 20° to left, and an offset angle of 20° to right respectively. In the following examples of practice, a tool is deflected to left.

(EXAMPLE OF PRACTICE 1)

The corner of the cutting part of a tool (hereinafter referred to as a straight turning tool) having an apex angle of 40° of the cutting part was found to have an arc-shape with a length of the chord approximately 1 μm by an observation using an optical microscope with 800 times of magnification. Accordingly, the shape of the corner of the cutting part was regarded as an arc of radius 0.5 μm. In this case, the distance from the virtual apex of the edge to the end point of the arc was 0.5 μm/sin20° = 1.46 μm, which

is within 3 μm. This straight turning tool was fitted to a

super-precision lathe (Fig. 3) with an offset angle of 20°,

was set in a manner such that the step section of diffractive

grooves is parallel to the optical axis of the optical

surface to be worked with an angular error of 1° or under,

and the diffractive optical surface of the metal die for a

plastic objective lens to be used for a DVD or a CD in either

way was cut-worked. On the other hand, with a straight

turning tool having rounded corner, which had been finished

to have a corner radius of the rake face 3 μm and a roundness

of 50 nm or under and was set at an offset angle of 20° to a

super-precision lathe, the diffractive optical surface of a

metal die for molding an objective lens having the same shape

as the above-mentioned for a pickup device was cut-worked.

The conditions of cut-working are the same for both. After

the measurement of the surface roughness Rz of the former and

latter metal dies obtained, the both metal dies were fitted

in the same die-fixture, and injection molding was performed

in completely the same conditions; thus, plastic objective

lenses of the same specification for both of a DVD or a CD

were obtained respectively. These objective lenses were

actually loaded in a pickup unit, and the amplitude of an

eye-pattern signal was measured for a DVD and a CD. The

results of the above-mentioned measurements were shown in
Table 2.

Table 2

	Surface roughness of metal die Rz	Maximum width of edge end /Width of diffraction	DVD signal amplitude	CD signal amplitude
Lens molded by metal die worked by straight tool	42.1 nm	3.8%	1.756 Vpp	1.323 Vpp
Lens molded by metal die worked by rounded tool	12.3 nm	21.1%	1.251 Vpp	1.278 Vpp

Although the surface roughness Rz of the worked metal
die worked with the straight turning tool is three times
worse than that of the metal die worked with the rounded
tool, light quantity loss owing to scattering is not produced
nearly at all. On the contrary, because the ratio of the
width of the imperfect-shaped portion to the width of the
diffractive grooves is nearly 1/6 of that for the rounded
tool owing to the corner radius R of the cutting edge being
three times sharper, diffraction efficiency is remarkably
improved; the amplitude value of the DVD signal which is more
influenced by diffraction light is improved by 29% more than
the metal die worked with the straight turning tool having
rounded corner. As the result of this, it was found that in

a metal die cut-worked with a straight turning tool, so long as the surface roughness Rz falls within a range from 1/1000 to 1/10 of the wavelength, and the ratio of the width of the imperfect-shaped portion to the width of the diffractive grooves cut-worked falls within a range from 0.5% to 15%, scattering is little, and a sufficient quantity of transmitted light could be obtained.

(EXAMPLE OF PRACTICE 2)

With a straight tool having an apex angle of 30° whose corner of the cutting part lies within 1.3 µm from the virtual apex position, the diffractive optical surface of a metal die for molding an objective lens for use in a pickup device using a light source wavelength of 405 nm was cut-worked. Before working, assuming the limit value of Rz was $\lambda/10$ (40.5 nm), the radius R in the case where the corner of the cutting part was regarded as an arc was calculated from the equation 2, to obtain 348 nm. From this value and the limit value of Rz, feed rate was calculated by using the equation (1), to obtain 244 nm/rev In accordance with these cutting conditions, the number of revolutions of the spindle and the tool feed speed were set at 2000 rpm and 0.5 mm/min respectively, and cut-working was carried out. After fitting the finished metal die in a die-fixture, injection

compression molding was carried out, to obtain a plastic

objective lens which had a low birefringence and was

excellent in the ability of transferring the shape of a metal

die. The measured quantity of transmitted light was 89.2%

without reflection reducing coating (the refractive index of

the material n_{400} = 1.55); it could be obtained almost an

ideal value as compared with the calculated value 9.3% (for

both surfaces) for the loss of light quantity owing to

surface reflection for perpendicular incidence.

(EXAMPLE OF PRACTICE 3)

By using a three kinds of tools, which were a first

straight turning tool having an apex angle of the cutting

part of 40°, a first clearance angle of 10°, and a second

clearance angle of 40°, a second straight turning tool of a

specification which was different from the first one in the

apex angle being 30°, and was the same as the first one in

other items, and a third straight turning tool having an apex

angle of the cutting part of 30° and asymmetric inclination

angles of the flanks of the cutting part, it was cut-worked,

the diffractive optical surface of a metal die for molding a

lens for use in a pickup device for a DVD, and the metal die

had the maximum normal angle 53° at its outermost

circumference, which was positioned outside the effective

diameter. A tool having an apex angle of the cutting part of
40° was attached to a super-precision lathe with an offset
angle of 20° to left in such a manner that the step section
of the diffractive grooves became parallel to the optical
axis of the optical surface to be worked with an angular
error not greater than 1°, and cutting was started from the
outermost portion of the metal die; however, it was found
that a cone-shaped optical surface was generated in the
outermost circumference portion, and the ridgeline of the
rake face and the flank interfered the metal die. Therefore,
the tool was switched over to the tool having the apex angle
of the cutting part of 30°, with the tool holder left as it
was, and the tool was fitted with an offset angle of 20°, to
cut-work; however, it was found that the ridge line of the
flank and the second clearance face was in contact with the
metal die. Then, the clearance angle of the second clearance
face was measured, to find 38.5°, which is slightly under
40°, and it was found that the tool interference was produced
for the reason that a tool having a small second clearance
angle owing to dispersion in manufacturing tools was used by
chance.

Therefore, an asymmetric straight turning tool having
an apex angle of 30° likewise, the inclination of flank of

the cutting part to the offset direction 0°, and the

inclination of the other flank of the cutting part 4.9° is

fitted to a super-precision lathe with an offset angle of 20°

to left, and the optical surface of a metal die was cut-

worked again. No tool interference was produced, and because

the clearance between the flank of the tool and the optical

surface was large, the elimination of the cut scraps and the

feeding-in of lubricant liquid could be sufficiently

performed; as the result, a high-quality optical surface with

less catching of chips was obtained. In this connection, the

inclination angle of the flanks of the cutting part of the

symmetric straight turning tool having the apex angle 30°

which produced tool interference was 2° for both left and

right sides.

From the above description, in the case of the tool

having the apex angle of the cutting part 40°, the normal

angle was 90° − (40°/2 + 20°) = 50°, which is smaller than the

maximum normal angle 53°; therefore, it was backed up that

tool interference was produced by the ridgeline of the rake

face and the flank. Further, in the case where the apex

angle of the cutting part is 30° and the offset angle is 20°,

the normal angle was 90° − (30°/2 + 20°) = 55°, it did not

occur that the tool interference was produced by the
ridgeline of the rake face and the flank, but because the
inclination angle of the flank of the cutting part was small,
the tool interference was produced by the ridgeline of the
flank and the second clearance face. However also in this
case, by making the inclination angles of the flanks of the
edge asymmetric, the clearance of the flank coming close to
the optical surface of the metal die could be made large, by
which the production of tool interference could be
suppressed.

(EXAMPLE OF PRACTICE 4)

By using an asymmetric straight turning tool having an
apex angle of the cutting part of 25°, an angle of
inclination of the second clearance face of 40°, an angle of
inclination of the right flank of 4.9°, and an angle of
inclination of the left flank of 0°, and an asymmetric
straight turning tool having an apex angle of the cutting
part of 25°, a first clearance angle of 10°, no second
clearance face, the ridgeline of the second clearance angle
formed by the intersection of the left and right flanks, a
second clearance angle of 40°, a first inclination angle of
4.9° of the right flank, a second inclination angle of 20° of
it, an inclination angle of 0° of the left flank, and no

second inclination angle, the optical surface of a metal die

for molding a diffractive objective lens having the maximum

normal angle 61.6° and the NA 0.85 for use in a pickup device

was cut-worked. It was understood that, for an offset angle

of 15°, the normal angle for both tools became 90° − (25°/2 +

15°) = 62.5°, then the tool interference by the apex angle of

the cutting part for the maximum normal angle could be

avoided; therefore, the tool was set at the offset angle 15°

to left to an super-precision lathe.

When the surface of a metal die was cut-worked with the

former tool, the ridgeline of the right side face and the

second clearance face interfered the metal die, and it

occurred not only that the diffractive optical surface could

not be generated, but also that the optical surface was

damaged to a large extent, which made it unable to use it by

reworking. Thus, a new piece of the same metal die was

prepared and cut-worked with the latter tool; then it was

found that tool interference was not produced and the cut-

working of the optical surface could be performed.

Regarding the flanks of the cutting part, only the one

side may have two steps of inclination, or the inclination

angle may be varied by 1° or more for the left and right

sides to make the shape asymmetric; further, also it is

appropriate that the flanks have a shape which is hard to produce tool interference by increasing the clearance of the tool owing to a synergistic effect through making the combination of these. The scope of this invention covers each of means for avoiding tool interference and also the combination of them.

According to this invention, by making definite the values and the ranges which are required for obtaining a sufficient quantity of transmitted light, it is possible to provide a metal die capable of actualizing the manufacturing of a diffractive optical element having a high efficiency, a tool for it, and an optical element manufactured by it.